Dedicated Indirect Searches for Dark Matter Using Antideuterons

1. Fundamentals of Dark Matter Detection with Antideuterons

1.1. Basic Idea of Antideuteron Searches

A number of years ago it was pointed out [1] (hereafter DFS), [2] that the antideuterons produced in WIMP-WIMP annihilations (the "primary" antideuterons) offered a potentially attractive signature for cold dark matter (CDM). The reason is that the spectrum of antideuterons is fairly flat over the 0.1-1 GeV/n energy band, while the "secondary" antideuteron spectrum (those produced in cosmic-ray interactions in the interstellar medium) sharply drops with decreasing energy. Thus a search for low energy antideuterons can have a very high signal (primary antideuterons) to background (secondary antideuterons) ratio. Indeed the background was so low at ~ 0.1 GeV/n that one could legitimately describe an experiment as background free. The antideuteron search for DM represents a major improvement over the well-established approach of searching for the WIMP-WIMP annihilation antiprotons. These primary antiprotons have a spectral shape and magnitude virtually identical to the secondary antiproton background. Indeed the available data from many experiments clearly established that the available antiproton data could be fit without any primary antiproton component [3].

Following the work of DFS an experiment was proposed – the General Antiparticle Spectrometer Experiment (GAPS). GAPS is the only experiment optimized solely for antideuteron searches. GAPS serves as a strawman for the scientific argument for antideuteron searches for CDM presented in this white paper. Both GAPS and alternate antideuteron search techniques are described below. GAPS is a balloon-based experiment, and is currently funded by NASA for a prototype flight in 2011.

Since the DFS proposal there has been much discussion in the literature of the "smoking gun" aspect of identification of CDM with antideuterons. In an interesting twist, Baer and Profumo [4] (hereafter BP05) noted that the detection of a single antideuteron in a GAPS balloon experiment provides higher confidence detection than on a GAPS satellite experiment. The latter, unlike the former, is sensitive enough to detect secondary and tertiary antideuterons, and thus cannot claim detection of DM with a single antideuteron. Thus a balloon-based experiment is a natural means to search for CDM. More recent analysis [5] suggests that the single antideuteron threshold for detection of CDM is probably overoptimistic because BP05 did not consider misidentification of non-antideuteron sources of background in GAPS. However the one count threshold does provide $\sim$ 98-99% detection confidence, and a few counts three sigma detection, depending on experiment details such as total observation time and background cuts.

2. Antideuteron Seaches: the Science Case

2.1. Direct and Indirect Detection Techniques

Several recent reviews echo a growing consensus that no single experiment can definitively detect DM [6, 7]. Rather, a range of experiments are required that yield a self-consistent picture of the candidate DM particle and its relevant mass and couplings. A more broad-based experimental approach is particularly crucial since theoretical prejudices can substantially alter interpretations of a given data set. Gondolo [8] has driven this point home in the case of the DAMA results, where comparisons with upper limits from other experiments are complicated by the need for theoretical assumptions about WIMP mass, halo model and the nature of the coupling to the target scattering nucleus. In addition, direct detection is not without complications; the issue of elastic neutron scattering – a process that can mimic the WIMP signature – is a continuing challenge for direct detection [9].

As pointed out in the above reviews, what is required is not only experimental confirmation from different direct detection experiments (eg. DAMA, CDMS, XENON) but confirmation from entirely different kinds of signals, and those signals need to be explainable with a self-consistent set of WIMP parameters. In this regard, the rich variety of indirect DM detection techniques is a valuable complement to the underground experiments. Because WIMP-WIMP annihilation is a fairly generic feature in beyond Standard Model physics, there are many signatures available. These include antiprotons, antideuterons, positrons, neutrinos and gamma rays. However few of these emanations meet Gondolo's [8] gold standard of having a signature due to WIMPS, and nothing else. Galactic observations by EGRET and INTEGRAL have detected excesses in high energy gamma ray and 511 keV gamma rays respectively. The positron bump detected by HEAT and PAMELA is another example. It is difficult to see how bumps or enhancements in poorly understood astrophysical backgrounds could ever stand as *independent* evidence of dark matter. The exception is GLAST or VERITAS, where a gamma ray line at very high energy corresponding to a massive neutralino, for instance, would provide a signature that cannot be imitated by any known astrophysical process. Nevertheless having a plethora of indirect approaches, even problematic ones, is potentially useful if a self-consistent picture across many experiments can be achieved. Arkani-Hamed et al. [10] have recently demonstrated that this is not entirely inconceivable even now, having reconciled DAMA with a number of "detections" in indirect experiments within the context of interacting dark matter.

2.2. Why Antideuterons?

There are a variety of reasons to pursue antideuteron searches. Firstly there is a sociological argument. There are a huge number of planned and active underground dark matter searches, and no dedicated antideuteron searches. From an experimental standpoint a better reason is that it is not easily confounded by its astrophysical background. However the most compelling arguments for a dedicated antideuteron search are its experimental reach (discovery potential) and its synergy with other DM searches. We discuss each of these points here.

2.3. The Reach of Antideuterons

BP05 comprehensively investigated a GAPS antideuteron search and a more recent analysis has been done in Donato et al. [11] (hereafter DFM). Both papers focused on WIMPS annihilating into $\overline{\mathrm{b}}\mathrm{b}$ pairs, since these give the largest yields among non-leptonic states, and because many bino-like configurations cover particularly interesting regions of minimal supergravity (mSUGRA). In addition BP05 looked at W^+W^- final states. They generally provide the lowest antideuteron signal among the non-leptonic final states. Within the framework of the MSSM this final state stands in for several important scenarios involving wino-like and higgsino-like DM. The above approach allows the antideuteron flux to be bounded in a fairly model-independent fashion, useful for understanding the capabilities of antideuteron search experiments.

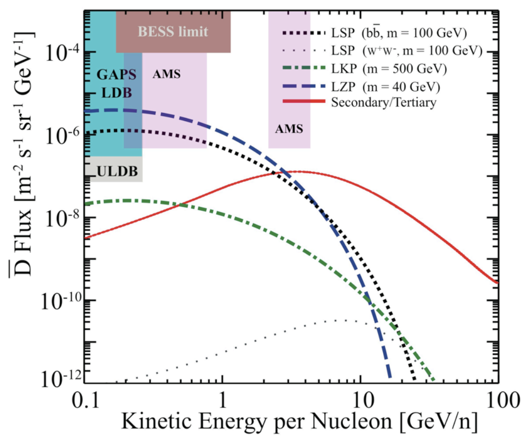

Figure 1. Sensitivity of BESS (current), AMS and GAPS antideuteron searches. The LSP, LKP an LZP are CDM candidates, as described in text. Background [12]; signals [4]; AMS sensitivity (DFS; [13])

Figure 1 shows the antideuteron flux from 4 different WIMP models as a function of antideuteron kinetic energy. Also shown is the (only) upper limit on antideuterons, obtained with the BESS experiment [14]. GAPS will exceed the BESS upper limit by more then 3 orders of magnitude. Also note that for a neutralino in the $\bar{b}b$ decay mode, or for the LZP (the lightest particle in a 5-d warped GUT model), which at the $\sim$ 40 GeV mass decays primarily through an s-channel resonance of the Z boson, an antideuteron signal is clearly detectable and at levels $\sim$ 50-100 times the background. While not obvious in this plot, we note the LZP is easily detectable in the $\sim$ 30-60 GeV mass range [4], and this is also the preferred mass range for an LZP consistent with the WMAP inferred CDM abundance. The lightest Kaluza-Klein particle (LKP) is not detectable with balloon GAPS. A satellite GAPS (not discussed further in the white paper) might be able to detect the LKP through low energy spectral fitting of the combined primary and secondary/tertiary antideuteron signal, but we have not yet studied this prospect. The W^+W^- decay channel provides a worse case, however the displayed neutralino is very heavy. At neutralino masses $\sim$100 GeV, the antideuteron flux from the $\bar{b}b$ channel and the W^+W^- channel are comparable [4] and detectable.

Another example of the reach of antideuteron searches, parameterized in terms of the neutralino mass, is shown in figure 2 [11]. The $\gtrsim$ 50 GeV neutralino masses are from a low-energy MSSM. The lower mass neutralino count rates originate in some non-universal gaugino models. GAPS can provide exceptional reach for probing such models, and very often in a region of SUSY parameter space consistent with the WMAP CDM relic density (red dots in figure 2). GAPS also accesses many regions of parameter space not consistent with the WMAP

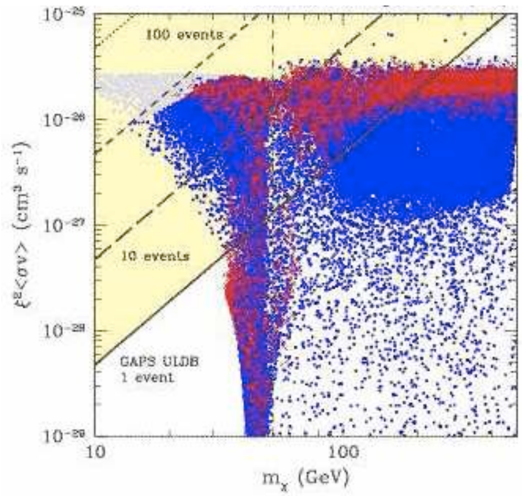

Figure 2. Sensitivity of a GAPS balloon experiment plotted in an effective annihilation cross-section neutralino mass plane for a low-energy supersymmetric model [11]. Models in red are consistent with WMAP CDM relic density.

inferred CDM abundance. This is also true for many models relevant to antideuteron searches not shown here. As most recently emphasized in a paper by Kane and Watson [15], the relic density predicted for a given model of CDM depends on numerous assumptions that are not particularly natural. Relaxing these assumptions to include processes such as non-thermal production, entropy production after freeze-out, non-radiation dominated expansion during DM production etc. should be considered. Thus considerable reach into these regions of parameter space excluded by the standard picture of thermal WIMP production and its corresponding relic CDM density is most important.

2.4. Antideuterons provide synergy with other search methods

We give some examples of how GAPS can work in synergy with other experments as discussed extensively in BP05 [4] and Profumo and Ullio [16]. Figure 3 is a quadrant plot [4] of count rate in CDMS-II (shown as an interaction cross-section), representing a canonical direct detection experiment, and the flux in GAPS. This analysis is for a particular neutralino in the general MSSM, and is very restrictive. It only covers models giving the thermal relic abundance for CDM defined by the WMAP range. In the upper right hand quadrant are models accessible to direct and antideuteron experiments. Within this region joint detection will provide better constraints on neutralino parameters than either technique alone. BP05 [4] emphasized the complementarity of direct and antideuteron searches. Many models not giving a large direct signal are detected by GAPS and vice versa. A similar quadrant plot and similar conclusions can be drawn comparing GAPS with IceCube [4], which searches for neutrino-generated muons. The neutrinos are produced in neutralino-neutralino annihilation in the sun [17].

Split-SUSY models also illustrate how GAPS works in synergy with other experiments. Split-SUSY models are well-studied, and perhaps most notable in that accelerator studies at

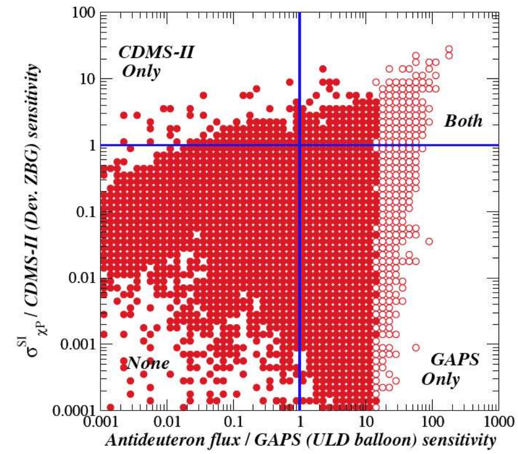

Figure 3. Quadrant plot of CDMS-II vs. GAPS sensitivity. Red points indicate MSSM models consistent with WMAP relic abundance [4]. Horizontal line is a CDMS sensitivity and the vertical line is a GAPS sensitivity.

LHC do not reach into the split-SUSY parameter space at all. Masiero, Profumo and Ullio [18] identified antideuteron searches (and GAPS in particular) as an essential probe of split-SUSY, capable of covering large regions of parameter space available to no other method and acting in synergy with other methods (eg. antiprotons, positrons etc.) to explore the entire parameter space.

This section has concentrated on very generic models that are useful for bounding the capabilities of a GAPS antideuteron search, but more than 80 papers have been published analyzing antideuteron searches for specific beyond SM physics cases.

3. Approaches to Antideuteron Detection

There are two approaches to antideuteron detection. The first is with mass spectrometers utilizing superconducting magnets. These spectrometer are augmented with additional detectors for time of flight, discrimination of leptons and hadrons and calorimetery. The current upper limit on antideuteron flux by the BESS experiment utilized such an instrument, as does the AMS-02 experiment, scheduled for launch on the shuttle to the International Space Station. Magnetic spectrometers are not optimal for antideuteron searches at low energies. Their sensitivity is limited by the need for very large magnets. And they are challenged by a background due to misreconstructed deuteron and antiproton events. An ultra-long duration balloon GAPS is $\sim$ 6-7 times more sensitive than a multi-year AMS-02 search for antideuterons [11, 13]. Moreover AMS-02 operates in a higher energy band than GAPS, so its mean secondary/tertiary antideuteron background is $\sim$ 3-5 times higher than GAPS. Nevertheless GAPS and AMS-02 offer complementarity, since the AMS-02 energy band extends from about the upper end of the GAPS band ($\sim$ 0.2 GeV/n) out to $\sim$ 1 GeV/n.

4. The GAPS Concept

The GAPS approach is discussed in detail in Mori et al. [19] (hereafter M02). We review the basic ideas here since it is less familiar than magnetic spectrometers. The GAPS concept is summarized in figures 4. An antiparticle that has been slowed down by the atmosphere passes through a time of flight (TOF) system (which measures particle velocity) and is slowed down by dE/dx losses in the target/detector. After stopping in the target, the antiparticle forms an exotic atom in an excited state with near unity probability. The exotic atom deexcites through both autoionizing and radiative transitions. Through proper target selection, the absorption of the antiparticles can be tailored to produce 3-4 X-rays in the cascade down to the ground state. Tailoring the X-rays to be $\sim$10-100 keV allows for collection with standard X-ray detectors. After X-ray emission, the antiparticle annihilates in the nucleus producing a shower (star) of $\sim$ 5-10 pions. The X-ray/pion emission occurs in less than a few nanoseconds. The X-ray energies, which depend only on mass and charge, and are precisely known from quantum theory, uniquely identify the antiparticle. Moreover GAPS is ideally suited to low energy antideuteron searches because it is easy to range out low energy ($\lesssim$ 0.2 GeV/n) particles.

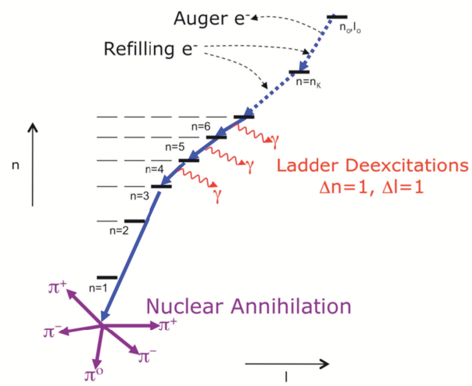

Figure 4. Sequence of deexcitations of an exotic atom leading to the characteristic radiation used to identify antimatter in the GAPS experiment [19].

The full particle identification – background rejection approach (illustrated for the most challenging case of antideuteron-antiproton) is shown in figure 5. In summary the process involves 1) simultaneous detection of X-rays emitted as the captured antiparticle makes atomic transitions from an excited state 2) TOF and depth sensing to distinguish heavier antideuterons from the lighter antiprotons and protons and 3) multiplicity of pions emitted from nuclear annihilation – on average, roughly proportional to the antiparticle nucleon number.

5. Development Plans

The basic GAPS concept was demonstrated in a series of experiments at the KEK accelerator in Japan [20]. GAPS is funded for a prototype flight tentatively slated for 2011 from the new Japanese launch facility in Hokkaido, Japan. A science flight is slated

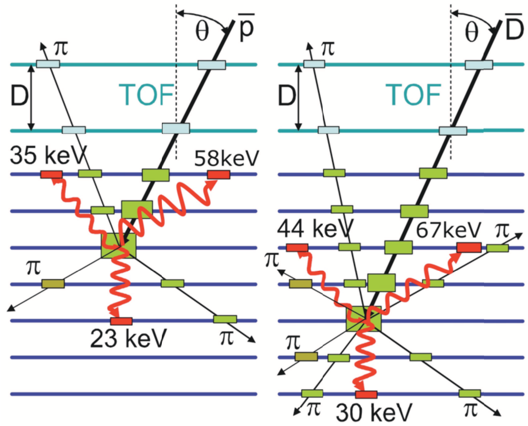

Figure 5. GAPS method of antiparticle identification. For the same measured TOF and angle (i.e., particle velocity), an antideuteron (right) will penetrate deeper, typically emit twice as many annihilation pions and emit X-rays of different well defined energies than an antiproton (left).

for 2014. More details about GAPS can be found in the papers referenced below and at (http://gamma1.astro.ucla.edu/gaps/index.html).

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